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Improving the Impact of Luminance Contrast on the Window Appearance in a Conventional Office Room: Using Supplementary Lighting Strategies

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Abstract: High contrast ratios between windows and surrounding surfaces could cause reduced visibility or discomfort for occupants. Consequently, building users may choose to intervene in lighting conditions through closing blinds and turning on the lamps in order to enhance indoor visual comfort. Such interventions increase projected electric lighting use in buildings. One simple method to prevent these problematic issues is increasing the luminance of the areas surrounding to the bright surface of windows through the use of energy-efficient supplementary lighting, such Light Emitting Diodes (LEDs). This paper reports on the results of a pilot study in conventional office in Brisbane, Australia. The outcomes of this study indicated that a supplementary LED system of approximately 18 W could reduce the luminance contrast on the window wall from values in the order of 117:1 to 33:1. In addition, the results of this experiment suggested that this supplementary strategy could increase the subjective scale appraisal of window appearance by approximately 33%, as well as reducing the likelihood of users' intention to turn on the ceiling lights by about 27%. It could also diminish the likelihood of occupants' intention to move the blind down by more than 90%.

Keywords: Window design; visual discomfort; office room; LED (light emitting diode).

1. Introduction

Office workers generally spend most of their working time inside the buildings in which they work (Schweizer *et al.*, 2007). It is well understood that improving Indoor environmental quality (IEQ) of office buildings can enhance work performance and reduce absenteeism of office workers, besides reducing energy consumption of buildings (Fisk *et al.*, 2011).

Indoor lighting quality as part of IEQ is one of the most significant attributes of a working environment (Ne'eman *et al.*, 1984). Optimal or at least acceptable indoor lighting quality, which relies on daylight and/ or electric lights, can be achieved through providing high level of visual performance and avoiding visual discomfort for occupants (Boyce, 2003).

Office buildings generally rely on vertical windows for daylight harvesting, particularly in high-rise cities (Huang *et al.*, 2014), and they are considerably favoured in working environments for access to daylight and an outside view (Veitch *et al.*, 1993). Vertical windows also characterise energy consumption and visual comfort patterns in buildings (Ochoa *et al.*, 2012). For instance, research suggests that a building with a typical façade, which has about 30% window to external wall, is likely to consume less energy than a building with fully glazed façade (Kevin Van Den and Meek, 2015).

The ubiquity of high contrast ratios between windows and the surrounding surfaces of the window especially when they are limited in a portion of wall can lead to reduced visibility and discomfort glare (Alrubaih *et al.*, 2013). Prolonged exposure to poor visual conditions may cause headache, visual stress, and eyestrain; besides negatively affecting satisfaction and productivity of office workers (Boubekri, 1995). Consequently, building users may intervene by closing blinds and turning on additional lamps to improve indoor visual comfort (Aschehoug *et al.*, 2000). For instance, a study among 123 buildings with installed photosensor-control systems illustrated that there is a comparatively monotonous relationship between the amount of illuminance from windows and turning on the lights by occupants, in particular when dimming control systems work perfectly (Heschong *et al.*, 2005). This study showed that as the window illuminance increases, the probability of switching on the lights will also increase to up to 60% to reduce luminance contrast between the window and surrounding areas. Evidently, occupants' interventions in lighting conditions increase electricity consumption of buildings.

The aim of this study is to improve user acceptance and visual comfort of typical day-lit offices, and to reduce negative occupant interventions in these spaces. It is presumed that one simple and efficient strategy to achieve this is to reduce the luminance contrast on the window wall by increasing the luminance of the areas surrounding the window using supplementary lighting, such as LED.

Preliminary small pilot study investigated potential energy saving offered by using supplementary LED system in a an office room (Amirkhani *et al.*, 2015). It evaluated subjective responses, as well as using the DAYSIM engine within ECOTECT to assess annual energy consumption of the test office room. The results of this study indicated that increased electricity usage of an approximately 18 W LED lighting strategy, which was not chosen because of its energy efficiency, is offset where there is roughly one-fourth reduction in users' intention to intervene in lighting conditions.

The purpose of this study is assessing subjects' acceptance for luminance ratios on the window wall under different lighting conditions using a simple rating scale (self-reported data). Physical lighting measurements are combined with occupant surveys to provide a better understanding of discomfort caused by high contrast ratios between windows and the surrounding window wall when they are in the field of view of occupants. In addition, different solutions that could reduce any apparent discomfort have also been tested. The results from this survey present valuable information for the design of more comfortable and glare-free office environments.

2. Method

2.1. Experiment settings

The experiments were conducted in an individual test office room on the first floor of a 2 storey building located in Brisbane central business distinct (CBD), Australia during June 2015. The test room is 3.17 m deep by 3.64 m wide and 3.85 m high. Figure 1 illustrates the plan and sections of this room. This room is facing South-West and its window has ceiling height at 3.6 m and a sill height at 1 m while the width of that is 1.23 m. The walls and ceiling are white and the flooring is grey. Daylight penetration is controlled by a fabric roller blind, and the room is furnished with a desk and chair, which are located in front of the window. This room has 2 x 28 W fluorescent luminaires, suspended 1.3 m from the ceiling. These luminaires can be switched on or off separately.

Cool-light LED strips, which have matched correlated colour temperature (CCT) to sunlight (5600 K-7000 K), were chosen to diminish luminance contrast in the field of view of subjects through distributing light on surfaces around the window. They were pre-assembled in a channel diffuser to reduce bright spots generally associated with strip LEDs and to distribute light evenly. Each of pre-assembled LED light strip has 30 mm width, 12 mm height, and 513 mm length. Each LED strip has luminaire power of 9 W and needs a constant-voltage driver to convert main voltage to 12 V. They were also equipped with a suitable compatible dimmer switch to be able to adjust light level from 0% to 100%. LED strip cases were mounted on the window sides with sill height of 2.1 m and the bottom of window surface (see figure 1). It should be noted that the proposed LED system in this study was chosen as merely an easy method to conduct the test and not for its energy efficiency.

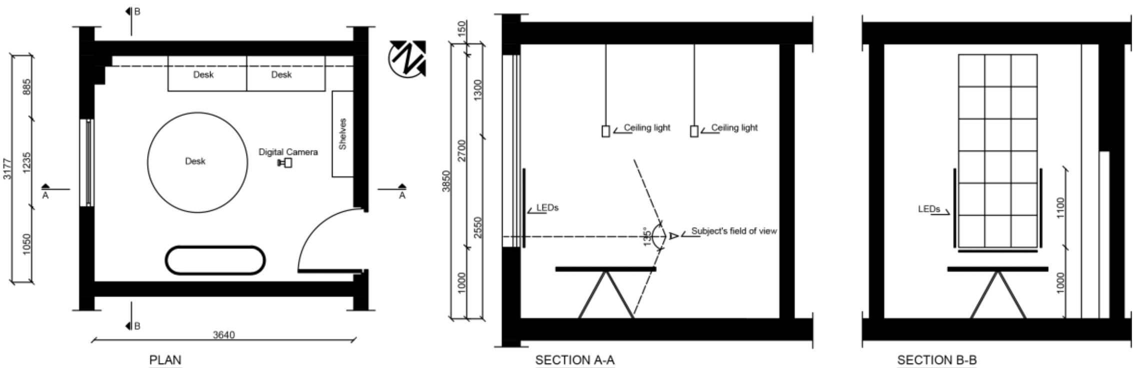

Figure 1: Plan and sections of the test office room in Brisbane, Australia

The test room relies on reflected sunlight (from adjacent buildings) and diffuse skylight for indoor daylight harvesting due to its orientation. Thus, the blind were fully opened during the experiment to have maximum indoor natural light.

2.2. Questionnaire

The survey was divided into three sections; date and time of conducting the experiment, basic demographic data from the subject, and some scales to rate participants' preferences for window appearance under different lighting conditions. The number of questions used in this survey was carefully considered to minimise fatiguing or boring the respondent, while still capturing the significant information required.

The second part of the survey collected demographic and personal information relevant to the participant's glare susceptibility. This included the participant's age, whether they wear corrective lenses, and whether the participant considers himself or herself as a glare-sensitive person.

The third section of the survey related to the participant's opinion and preference on the lighting in the test room. It was divided into four stages: no supplementary lighting, and LED wall-washing of the window surrounds at 3 different power levels (9 W, 18 W and 27 W). The questions in each stage were designed to find whether the use of the supplementary lighting system influenced feeling discomfort glare from windows and subjects' decision to turn on top lights.

It is frequently challenging to find predictable practical relationships between physical stimulus and subjective reaction in the field of lighting (Houser and Tiller, 2003). However, some studies have grouped perceived discomfort glare from daylight into bins of imperceptible, perceptible, disturbing, and intolerable (Suk and Schiler, 2013). The first question at each stage asks participants to rate the level of perceived discomfort glare from the window when it is in their field of view among these four groups.

Currently, there are different techniques that can be used to relate subjective responses to physical parameters in lighting research, including questionnaire, rating scales, magnitude estimation strategies, and paired comparison (Tifler and Rea, 1992; Houser and Tiller, 2003). However, according to Houser & Tiller (2003) paired comparison and semantic differential (SD) scaling are two of the most widely techniques used in lighting research. SD consists of a set of bipolar adjectives. The ends of each scale are defined through polar opposite adjectives which are separated through a seven-point scale (Monette *et al.*, 2013). The number of points to the scale can be varied between seven, five, or even three (Barbara Sommer, 2006). Therefore, the second question at each stage uses SD scaling to rate indoor visual comfort on a scale of 1-5 (one meaning very dissatisfied and five meaning very satisfied).

The last two questions at each stage ask subjects whether they want to move the blind down or turn on the ceiling lights (yes/no answer). If they respond yes to turn on lights, further question asks how many they would like to switch on (one or both of the ceiling lights).

2.3. Procedure

Thirty five people participated in this investigation and they were surveyed individually in the test office room. They were office workers with normal or corrected to normal vision and representative in age and sex of the general office worker population. Before starting the experiment, each subject was clearly informed of the purpose of the research, and shown the light measurement equipment. Each participant was asked to sit facing the window, around 2.2 m from the window surface and the experimenter stood somewhat behind the subject. They were also asked to fill the first and second section of the survey themselves; while the researcher led the remainder of the survey, adjusting light levels and asking questions for a verbal response from the participant.

To start the first stage of each experiment, all the ceiling lights and the LED supplementary system were switched off. The experiment followed the same process during each stage, whereas the luminaire power of the LED supplementary system was increased by 9 W at the start of stages 2 to 4. Participants were given one minute to adapt to light level changes before the survey started at each stage. Quantitative data was collected using a Nikon Coolpix 8400 digital camera (calibrated for luminance measurement (Coyne *et al.*, 2008)), Konica Minolta LS100 luminance meter, and Konica Minolta T-10 illuminance meter prior to asking the questions of each stage.

The digital camera was used to take High Dynamic Range (HDR) images to observe the luminance distribution at the window and surrounding surfaces. In order to capture a field of view that is relatively similar to human eye, an FC-E9 fisheye lens (focal length = 5.6 mm, 190° field of view) was used. The camera was located as practicable as possible to the head of subjects through using a tripod. Multiple pictures of the same scene were captured during each experiment to achieve a single HDR image with relative luminance through using Photosphere. In addition, the luminance meter (LS100) was used to measure the luminance value of a single white spot inside the room for HDR calibration in Photosphere.

Photosphere remembers the response curve of camera and attached lens. Therefore, it was not essential to measure luminance values of more than one spot. The illuminance meter was used to record the illuminance measurement on the working plane (the desk in the test room), which was 0.72 m above the floor and 1.5 m from the window. After collecting quantitative lighting information at the beginning of each stage while the participant was adapting to the change in lighting, the experimenter completed the questionnaire by directly asking the survey questions of the participants.

3. Results and discussion

Table 1 illustrates mean illuminance measurements at the desk level during each stage. There was a little variation in exterior lighting conditions across all experiments. For example, the mean standard variation of horizontal illuminance at the desk level across all test conditions was 18. Accordingly, about 95% of values were less than 36 lux away from the mean illuminance measurements during each test condition.

Table 1: Mean horizontal illuminance at the work plane level during each stage

Stage	Ceiling lights are off		One Ceiling light is on		Two Ceiling lights are on	
	mean illuminance (lux)	Std. deviation	mean illuminance (lux)	Std. deviation	mean illuminance (lux)	Std. deviation
1	159	13	250	21	384	25
2	160	15	251	21	385	23
3	169	17	261	18	397	19
4	180	18	275	17	409	14

Calibrated HDR images of each stage of all experiments were resized for calculation. Figure 2 shows an example of a HDR image captured by the digital camera when overhead lights and supplementary system were off. This image shows the 12 areas that were targeted for luminance spot measurements using calibrated HDR images, as well as the illuminance meter located on top of the desk. To obtain the value of the window to wall luminance ratio, readings 1 to 6 are averaged (to give window luminance) and compared to the average of readings 7 to 12 (for the surrounding wall luminance). These ratios are presented in table 8 below.

Figure 2: Captured HDR image from the test office room

Table 8 illustrates that as the luminaire power of proposed LED system increases, the luminance contrast between the bright surface of the window and surrounding walls decreases by about 72% and 81% during stage 3 and 4 to compare with stage 1, respectively.

Table 2: Mean luminance ratio between window and surrounding areas during each stage

Stage	Mean window luminance (cd/m2)	Mean wall luminance (cd/m2)	luminance ratio
1	2331	20	117
2	2406	38	63
3	2192	66	33
4	2289	103	22

Figure 3 plots participants' response for feeling discomfort glare from the window at the beginning of each stage during 35 experiments. It illustrates that the spread of variables during stage 1 generally fall within disturbing and perceptible, whereas the middle half responses for feeling discomfort glare falls within perceptible and imperceptible during stage 3 and stage 4. In addition, this figure indicates that although the median report for feeling discomfort glare during the first three stages remains the same and is perceptible, it is imperceptible during stage 4. Furthermore, only one person reported intolerable discomfort glare from the window throughout all stages. Overall, this figure suggests that feeling discomfort glare from windows can be reduced by about 33% through using proposed LED lighting system.

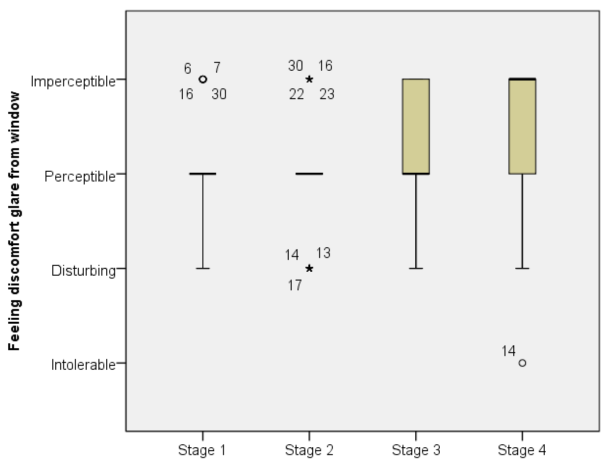

Figure 3: Boxplot of feeling discomfort glare during each stage

Figure 4 and 5 show the mean subjects' scores of indoor visual comfort at the begging of each stage and also in association with reported discomfort glare from window. Figure 4 shows that participants' satisfaction of indoor lighting level increased by around 17% and 24% throughout stage 3 and 4 in comparison with stage 1. Figure 5 illustrates that the mean participants' satisfaction for indoor visual comfort improved by 24% when they did not feel discomfort glare from the window in comparison with when their responses for feeling discomfort glare from the window was disturbing. Finally, these line graphs indicate that the mean score (about 3.7) for indoor visual comfort during stage 4 is similar to when reported discomfort glare from windows is imperceptible.

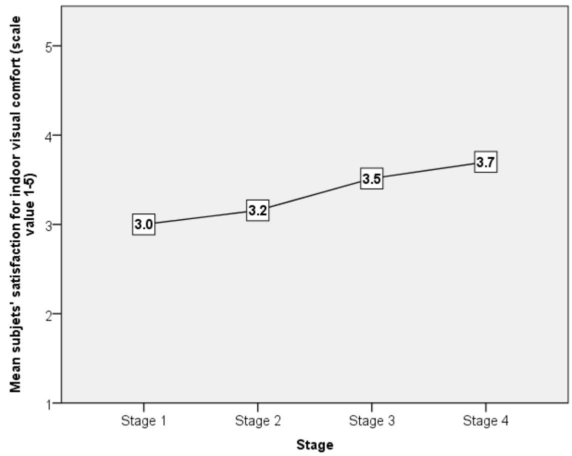

Figure 4: Mean subjects' satisfaction for indoor visual comfort during each stage

Figure 5: The relationship between mean subjects' satisfaction for indoor visual comfort and their responses for feeling discomfort glare from the window

Figure 6 plots luminance ratio on the window wall when subjects' response for feeling discomfort glare from window is intolerable, disturbing, perceptible and imperceptible. It indicates that subjects did not report discomfort glare from window when the median luminance contrast between the window and surrounding surfaces is about 32, which is close to the mean and median window wall luminance ratio during stage 3 (around 34 and 31 respectively).

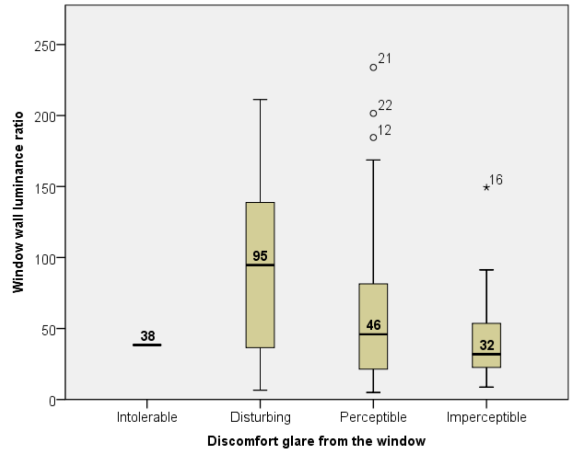

Figure 6: Boxplot of window wall luminance ratio and feeling discomfort glare from window

The results of the survey shown in figure 7 indicate that decreasing the luminance ratio between the window and immediate walls affect participants wanting to whether switch on or off top lights or to close blinds. This study suggested that the mean possibility of subjects' intention to turn on one or both ceiling lights decreased by about 27% when their responses for feeling discomfort glare from window were imperceptible. Approximately 53% of subjects wanted to turn on both overhead luminaires when they perceived discomfort glare from window. However, only 23% of subjects wanted to turn on both ceiling lights when they did not perceive discomfort glare from window. Figure 7 also indicates that the probability of moving the blind down decreased by about 77% and 97% when subjects' responses for feeling discomfort glare from window were perceptible and imperceptible to compare with when it was intolerable. In addition, the likelihood of moving the blind down diminished by about 96% when participants did not feel discomfort glare from window in comparison with when their responses for feeling discomfort glare from the window were disturbing.

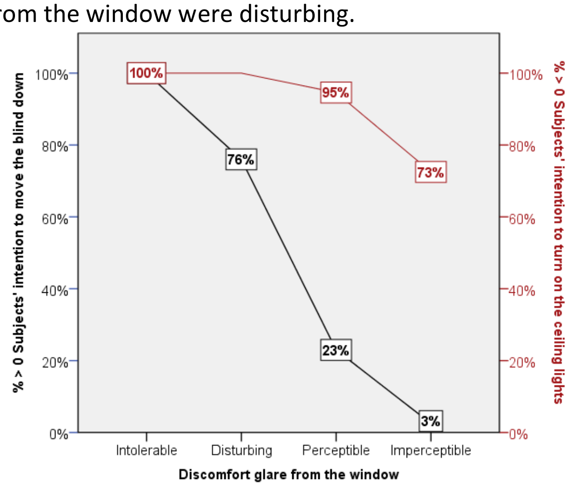

Figure 7: Survey results

Table 3 shows some demographic data of participants, including the number of participants who wore corrective lenses, participant age, and how many considered themselves to be glare sensitive. The results suggested that there is no relationship between responses of subjects who wore prescription glasses and who did not wear for feeling discomfort glare at the beginning of each stage. The results also did not indicate any significant relationship between age and reported discomfort glare in the test room. In addition, there is not any significant difference between the responses of subjects who considered themselves to be glare sensitive person and those who did not.

Table 3: Demographic data of participants

Question	Options	Number of subjects	Percentage	Median response
Prescription glasses	Reading	4	11.5	All the time
	Driving	3	8.5	
	All the time	11	31.5	
	Never	17	48.5	
Age	Less than 30	19	54.5	Less than 30
	Between 30 and 50	13	37	
	Between 50 and 65	3	8.5	
	More than 65	0	0	
Glare sensitive	Yes	22	63	Yes
	No	13	37	

4. Conclusion and future work

This study investigated users' acceptance for the luminance ratio on the window wall using a supplementary lighting strategy. A simple LED system was proposed for the supplementary lighting strategy. The main aim of this study was to test the impact of proposed LED system on subjects' intention to intervene in lighting conditions through moving the blind down or turning on the ceiling lights. The results from this study indicated that the proposed LED system could significantly diminish the luminance contrast between the window as a daylight source and surrounding surfaces by about 3.6 fold (from 117 to 33) during stage 3 and around 5.5 fold (from 117 to 22) during stage 4. The study also suggested that the mean indoor visual satisfaction increases by about 24% when the luminance ratio of window to wall reduces from values in order of 117:1 during stage 1 to 33:1 during stage 3. In addition, the results of this research indicated that the median report of discomfort glare from the window is imperceptible, while using proposed LED lighting system with approximately 18 W luminaire power (stage 3). Consequently, the mean users' intention to switch on ceiling lights diminished by about 27% and to move the blind down by more than 90% through using a supplementary LED strategy with about 18 W luminaire power. Furthermore, this investigation indicated that there is a monotonous relationship between feeling discomfort glare from windows and indoor visual comfort.

The tests in this study were not conducted randomly. This research also focused on a small conventional office room without any specific daylighting system. Further study is needed to investigate on more rigorous testing of occupants' perception using supplementary strategies in various test office environments with different office layout and window types. In addition, more investigation is needed to improve the energy efficacy of proposed supplementary system to considerably increase the energy savings available for this design system.

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